Acoutect Demonstrator for Open Plan Spaces

ACOUTECT

A case study on workstation dependent acoustic characterization of open plan offices

January, 2021

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CHAPTER 1

Problem definition

Open-plan space is used in interior building design to create shared functional environments. The basic idea is to foster flexibility, cooperation and spaciousness in indoor environments by eliminating any boundaries hindering sight and speech intelligibility, such as walls. However, the complexity of sound propagation in open-plan spaces makes acoustic modelling a particularly challenging problem. Moreover, in open-plan offices (see Figure 1) the acoustic environment is a mixture of machine- and human-made sounds. Thus employees often feel annoyed by various types of acoustic noise. Examples for typical noise sources are speech, walking sounds, environmental noise and working sounds (eg. typing

Figure 1: Photograph by VeronicaTherese: **The RedBalloon office** - an example of an open-plan 'Bullpen'-style office, Wikimedia Commons, distributed under a CC BY-SA 3.0 license.

on keyboards). In contrast to the intention of increased cooperation, for tasks requiring high levels of concentration the acoustic situation of the open-plan space is a drawback. Consequently, a number of studies have begun to examine employees' responses to acoustic noise. At the same time, it is unclear which acoustical treatment is better for open-plan spaces in order to improve the well-being in the working environment. The common practices include applying sound absorbing (meta-) materials on ceilings and baffles or screens, or applying sound masking.

It is greatly acknowledged that sound and vibration noise is addressed as an important factor in job satisfaction ratings, which is closely related with perceived health conditions. Therefore, it is important to reduce noise annoyances which may impair cognitive performance. However, the acoustics in open-plan offices remain often an unquantified issue. Even in cases where the acoustics are taken into account it is difficult to relate objective acoustic measurements to the employees' subjective feeling. As a result, in many cases measures to improve the acoustics are not targeted on a precise issue.

Occurrence of the problem

Since the upcoming of the open-plan office concept in the 1950s many companies have adopted such an office layout for their employees. A recent survey stated that 58% of the questioned employees in industrialized countries with office based jobs (276 422 persons) work in open-plan office environments. Furthermore, employment statistics suggest that in 2018 81 million people in the European Union work in office based jobs. (Population: 514 million, Population in working age: 64.7%, Employment rate: 72.2%, Employment in mainly office based sectors: 33.9%, source: https://ec.europa.eu/eurostat/home)

Therefore, the number of people working in open-plan offices in the European Union can be estimated roughly to 47 million. Assuming an average of 30 people per open-plan office approximately 1.5 million open-plan offices are in use in the European Union.

Naturally, acoustic annoyance is subjective and not every employee in an open-plan office feels discomfort. However, multiple studies suggest that comfort and productivity decrease in open-plan offices compared to ordinary office layouts. Moreover, surveys report that noise in open-plan offices is considered by employees as the main source of discomfort. Consequently, the acoustics in open-plan offices affect a significant amount of people and it is worth looking into improvements.

State-of-art

In acoustic consultancy, the specific problems in open-plan offices are usually diagnosed via complaints from the employees. The acoustic quality of the space is then quantified with in-situ measurements of acoustic parameters which are described in the ISO3382-3:2012 standard. These acoustic parameters notably include the privacy radius (distance above which the speech transmission quality is below 20%), the background noise and the decay rate of the sound pressure level over distance.

Based on these measures, actions can be taken to improve the acoustic environment. Usually, these actions aim to obstruct the unwanted sound propagation by placing absorbing

Figure 2: *Open-plan office with acoustic barriers*. Photograph by Asa Wilson - CubeSpace / Cubicles in a now-defunct co-working space in Portland, Oregon. / Wikimedia Commons, distributed under a CC BY-SA 2.0 licence.

surfaces in the open-plan office, most commonly on the ceiling or walls, but also by setting up acoustic barriers (e. g. cubicles in Figure 2) or screens in between workstations. Another approach is to improve acoustic privacy by sound masking, i.e. by creating a non-distracting, low-level background noise soundscape (e.g. with white noise or flowing water sounds). Simulation software is usually the main tool to design these actions. Most of the time, simple down-to-earth actions, such as a noise-awareness policy or a rearrangement of the office's layout, can also be effective without additional equipment. Last but not least, another issue is that little to no attention has been paid on the effect of walking sound in open-plan spaces. While the ISO standard introduced human-made sound, it addresses only speech-related measures. However, the average consultancy approach usually lacks further investigation especially on noise perception, and improvements usually rely on a trial-and-error method.

Approach

Our approach to investigate human perception with respect to common open-plan office treatments is based on interdisciplinarity. This is at the very core of the demonstrator, including the fields: "design, product, evaluation". Following the aforementioned three-fold model our aim is to develop a methodology based on acoustical measurements and simulations followed by perceptual evaluations (Figure 3). Our study is focused to intertwine acoustic measurement with acoustic simulations to evaluate the effect of different acoustical treatments on subjective perceptual evaluations.

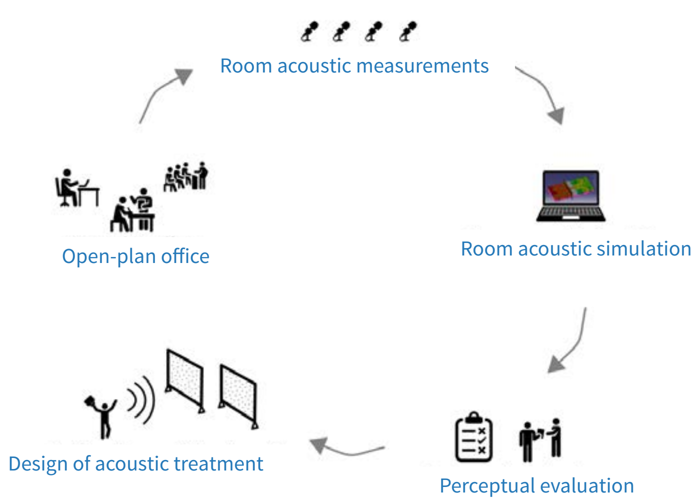

Figure 3: Demonstrator high-level schematic

Furthermore, we will employ numerical simulations to bridge the gap between in-situ acoustical measurements and sound propagation models. Concretely, we will conduct a simulative study on the effects of acoustic treatment in the open office. Based on the simulated data we will design and conduct a listening test to obtain subjective responses.

The benefits of this holistic approach are multidimensional. This is because they may produce new knowledge that can be used by acoustic consultants or fertilize the development of an industrial product or an academic contribution.

Details of the specific problem

The demonstrator of our study is an open-plan office at Siemens Industry Software NV in Leuven, Belgium (Figure 4). The office has been designed for 24 workstations, its dimensions are approximately 14 m x 11 m x 2.7 m and it is furnished with limited acoustical treatment (i. e. ceiling, floor covering and a few acoustic screens). Employees who work daily at this office report acoustic annoyance and limited acoustic privacy. As it can be seen in Figure 4, the workstations in the office are grouped into six islands of four workstations each. The distance between islands is relatively small (1 - 2 m). The only sound-soft surface in the office is the floor carpet.

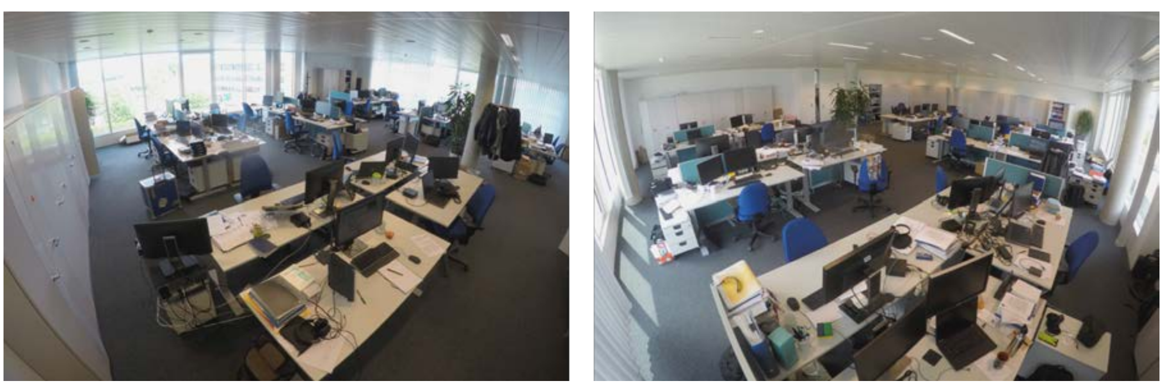

Figure 4: Office at Siemens Industry Software NV (Leuven)

A road is located close to the building in which the office is located, but the office itself is situated on the side of the building not facing the road. Therefore, road noise is not audible inside the office. The sources of noise in the office were identified as the employees themselves via talking or loud keyboard typing as well as background noise from ventilation systems. As a non-intrusive treatment the deployment of further acoustic screens could be a straightforward way to improve the situation. However, details such as positioning of the screens and the screen height need to be assessed first. These questions shall be answered in our study.

CHAPTER 2

Description of the measurement method

We performed measurements in the open-plan office outside office hours in order to:

- obtain transfer functions / impulse responses between workstations for auralization and perceptual tests
- characterize the office acoustics
- obtain a reference dataset for comparison with our upcoming simulations

To this extent, we equipped each workstation on the height where the ear of a human working there would be situated, with a GRAS 40PH CCP Free-field microphone as receiver. Because in the office situation every workstation (every human) acts both as sound receiver and sound source we used a movable, omnidirectional LMS Q-source loudspeaker as excitation (the source, Figure 1).

In order to obtain transfer functions from all source-receiver combinations we placed the source at each workstation and performed a recording. We used a chirp in the frequency range of 20 to 20.000 Hz as an excitation signal. However, the loudspeaker allowed a reasonable signal to noise level only in the range of 150 to 5.000 Hz. The recordings were operated

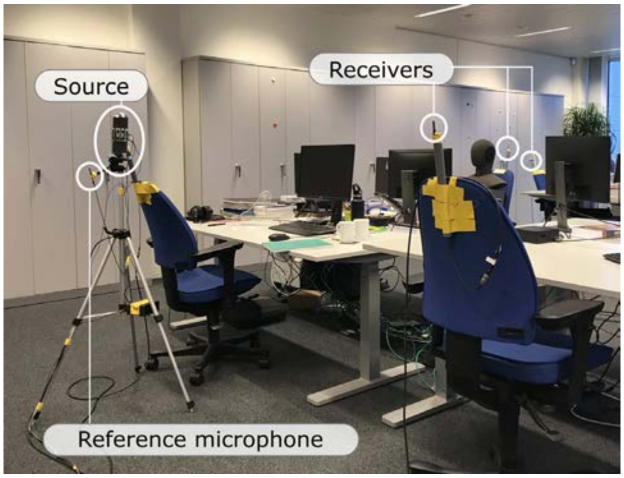

Figure 1: Measurement method

with the software Siemens Test.Lab and a SCADAS data acquisition system was used. While measuring the transfer functions, we recorded simultaneously binaural data with a HEAD acoustics HMS IV head and torso simulator (HATS) located at a single workstation.

In addition, we performed the line measurements described in ISO 3382-3:2012 for a characterization of the office acoustics as well as measurements with a burst signal for evaluating the reverberation time of the room.

Office impulse responses, room acoustic parameters and sound level decays

From the 24x24 measured impulse responses the room acoustic parameters for open-plan office (as defined in the ISO 3382-3:2012) were extracted. In a first step, the curves of sound level decay and speech intelligibility index (STI) decay with respect to distance were calculated for each source position. From the sound level decay curves, the parameters of sound level attenuation per doubling distance ($D_{2,S}$) and the A-weighted sound pressure level of speech at 4 meters ($L_{p,S,A,4m}$) are computed. Furthermore, from the STI decay curves, the distraction radius (r_D) and privacy radius (r_P) are calculated. Those parameters represent the distance at which the STI becomes less than 0.5 and less than 0.2, respectively. The calculation of these four room acoustic parameters was done for each source position. The average, minimum and maximum of the values obtained are shown in Table 1.

Parameter	Minimum	Average	Maximum
$L_{p,S,A,4m}$(dBA)	48.5	49.5	50.3
$D_{2,S}$ (dB)	3.5	4.4	5.2
r_D (m)	11.3	13.6	17.1
r_P (m)	19.0	23.8	30.6

Table 1: Variations of room acoustics parameters across the office.

It can be seen that $L_{p,S,A,4m}$ and $D_{2,S}$ do not vary a lot depending on which workstation is the source of noise. However, the variations regarding the privacy and distraction radiuses are much greater. This suggests that the speech intelligibility in the room is dependent on the location of the speaker. It can also be noted that the privacy radius is always greater than the dimensions of the room, meaning that speech will always be somewhat intelligible from any workstation to another. This result was expected given the relatively small dimensions of the office and the absence of obstacle to the propagation of sound.

Furthermore, the average reverberation time measured in the octave bands relevant for speech signal (i.e. 500, 1000 and 2000 Hz) are shown in Table 2. These values will be used to realize a computer simulation of the office.

Octave band	500 Hz	1000 Hz	2000 Hz
Reverberation time (s)	1.59	1.44	1.15

Table 2: Average reverberation times across positions measured in the office in the 500-1k-2k Hz octave bands.

How room acoustic conditions may influence psychoacoustic annoyance

The analysis of the in-situ acoustic measurements showed that the distraction distance is as large as the size of the office. In other words, any human speaker in the office will be heard and clearly understood by all the other employees. Speech is widely acknowledged as the most significant distractor in open offices and is also correlated with differences in perception of acoustic annoyance and abatements of work performance. Thus, if no acoustic treatment is installed, then the acoustic performance of the office will have negative effects on the acoustic distraction of the employees.

Psychoacoustic annoyance is a multidimensional subjective percept. That is, it depends on a combination of objective measures like loudness, sharpness, roughness and more. Thus, the statistical inter-dependency between these objective measures suggests that annoyance is not a one-dimensional scale. Furthermore, annoyance has been shown to correlate with individual characteristics, like neuroticism, which adds more complexity towards a standardized quantification technique.

Typically, annoyance ratings are collected using self-reports, which besides any drawbacks forms the only way to capture the first level of subjective experience. We can measure psychoacoustic annoyance using the so-called Likert scales (or affective scales), but it is also possible to use AB comparisson. Likert scales are convenient tools to measure multidimensional percepts, though difficulties arise when an absolute ranking is the desired goal. Ranking is used in acoustic quality to evaluate the acoustic performance of a product. For such applications another kind of comparison is recommended (ABX, with a no-opinion choice) and it can be used to evaluate one-dimensional percepts like loudness and tonality.

Computer simulation

The goal of this study is to combine measurements, computational methods and listening tests to implement an effective treatment of an open plan office. To this end, a geometrical room acoustic model is employed to reproduce the impulse response for each source-receiver configuration (see Figure 2).

In the geometrical acoustic methods, simplifying assumptions regarding sound propagation and reflection are being made, and sound propagation is considered as sound rays along which the acoustic energy is transported. This makes it a valid and accurate approximation for the sound propagation in the high frequency range. Although geometrical acoustic methods are computationally fast, its inherent nature directly deteriorates the simulation accuracy of complex wave phenomena such as interferences, scattering and diffraction, especially in the low-frequency range. However, since speech is the main type of sound nuisance in this work and the geometry of the office does not show any problematic feature, such phenomena are limited and a geometrical acoustic simulation is considered sufficient.

We created the computer model of the office with the software Google Sketchup, using the geometrical measurements performed in-situ. The geometrical model was then imported to the Odeon software for geometrical acoustic computations. We estimated the acoustical absorption coefficients of the surfaces of the model based on observations and typical values found in the software documentation. The absorption coefficient of the most absorbing surface, the floor's carpet, was then slightly adjusted to match the measured reverberation time of the office in the 3 octave bands 500-1k-2k Hz. This computer replica of the office is the base of the treatment simulations realized subsequently.

Figure 2: View of the office's computer model, with workstation numbers.

CHAPTER 3

Simulation of acoustical treatment

We introduced acoustic screens of various heights *H* in the computer model of the office. Three heights of screens were considered: 110 cm, 140 cm and 170 cm. The height *H* represents the total height from the floor to the top of the screens. For each treatment case, screens are dividing all workstations within desk islands, as well as the sides of the islands, as pictured in Figure 1.

The absorption coefficients chosen for the screens are compatible with a thin layer of porous material. The random incidence absorption coefficient chosen to model the absorption of the screen in the simulation software is displayed in Table 1.

For each of the 3 heights of screens introduced in the computer model of the office, binaural impulse responses (BRIRs) are computed for two representative receiver workstations (no. 9 and 22) and six representative source workstations (no. 2, 6, 11, 16, 19 and 21), resulting in twelve BRIRs per treatment.

Octave band	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Absorption coefficient (s)	0.04	0.06	0.17	0.34	0.45	0.63

Table 1: Random incidence absorption coefficient used in Odeon to model the porous screens.

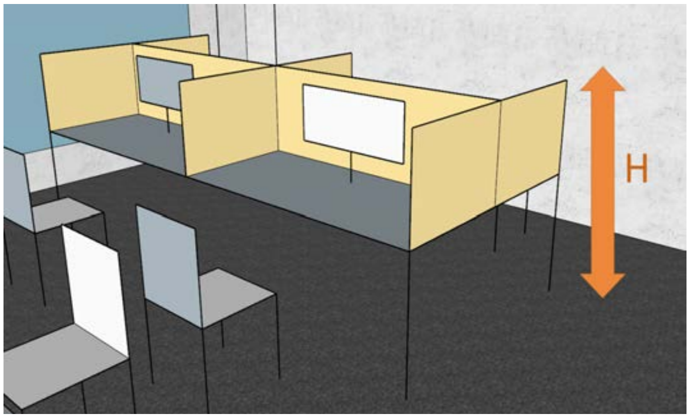

Figure 1: Disposition of acoustical screens within one desk island in attempted treatments.
The screen height on the picture is H = 1.4 m.

Listening test

We conducted a web-based listening test to evaluate the effect of different screen heights on acoustic annoyance. Our aim was to evaluate the optimal screen height for the demonstrator office. The design was a two-alternative forced-choice based on replacements without repetition. We selected a forced-choice design in order to compensate for the limited control over the conditions during a web-based experiment (e. g. sound level, environmental noise). No assumptions were made about which screen heights might be sounding more annoying. Three screen heights (110, 140 and 170 cm) along with the untreated version of the office (0 cm screen height) were evaluated using paired comparisons.

Our hypothesis, "The responses of the listening test will vary with respect to stimuli based on different screen heights.", was statistically evaluated in the listening test. A total of 72 paired comparisons of speech stimuli was presented to the participants. The stimuli were based on binaural auralizations of one speaker (male, female) from the Harvard speech corpus. We instructed the participants to imagine that they are working in an open-plan office and trying to focus on their job. Furthermore, the participants were instructed to use headphones and to evaluate the overall impression of the virtual office design and not the particular heard voice.

Results

The listening test operated on BeaqleJS and was hosted on a server provided by Chalmers University of Technology. We evaluated a sample of 29 participants in the analysis (5 female, 24 male, age = 34.6+/-9.5 years old). Four participants were excluded from the analysis because they did not use headphones and one participant because of a declared hearing impairment. One more participant was excluded because his responses were inverted, thus he most likely responded to the annoyance as a preference test. On average, the participants needed 17 minutes to complete the test.

8 participants reported no work experience in open-plan offices and 21 had work experience in an open-plan office (defined as an office with six or more employees). Interestingly, a significance test between the two populations showed strong statistical evidence that the perception of the two populations with regard to the presented sounds differs (chi-

squared = 32.7101, p-value = 1.0698e-08). Overall, this statistical result corresponds to a tacit preference of the employees with work experience in open offices for larger screen heights. It seems like the employees used to open-plan office conditions attribute a higher value to an increased amount of acoustical treatment (see Table 2).

Number of participants	s00s11	s00s14	s00s17	s11s14	s11s17	s14s17	Total
29 participants	0.8420	0.9253	0.9713	0.6810	0.8448	0.8017	0.8443
R09 (29 participants)	0.9310	0.9425	0.9770	0.7816	0.8218	0.7529	0.8678
R22 (29 participants)	0.7529	0.9080	0.9655	0.5805	0.8678	0.8506	0.8209
8 (no work experience)	0.7083	0.8438	0.9167	0.6458	0.7917	0.7188	0.7708
21 (work experience)	0.8929	0.9563	0.9921	0.6944	0.8651	0.8333	0.8274
[R09] 8 (no work experience)	0.8958	0.9167	0.9583	0.7083	0.7292	0.6458	0.8090
[R09] 21 (work experience)	0.9444	0.9524	0.9841	0.8095	0.8571	0.7937	0.8902
[R22] 8 (no work experience)	0.5208	0.7708	0.8750	0.5833	0.8542	0.7917	0.7326
[R22] 21 (work experience)	0.8413	0.9603	1.000	0.5794	0.8730	0.8730	0.8545

Table 2: Proportions of how likely a shorter screen is rated as more annoying. sXXsYY refers to a comparison between XX decimeter screen height and YY decimeter screen height.

Figure 2 shows how likely it is that the participants report shorter screens as more annoying. Every category contains a total maximum of 12 stimuli per participant. For example, for both receiver positions R09 & R22 (see Figure 3) the number of stimuli per category is 12, whereas for the position R09 alone the number of stimuli per category is six. As a result of single receiver positions, the standard error of the binomial proportions is larger in comparison to both receiver positions.

The very nature of forced-choice responses does not allow for a direct comparison between categories of multiple screen height comparisons. An overview of the standard errors shows that the paired comparison between screen heights 110 cm and 140 cm (s11s14) is close to chance levels. This is particularly the case for receiver position R22. Overall, the results specific to workstation R09 and R22 show differences in the proportions for the preference of a higher screen. This indicates that the perceived annoyance is location-specific.

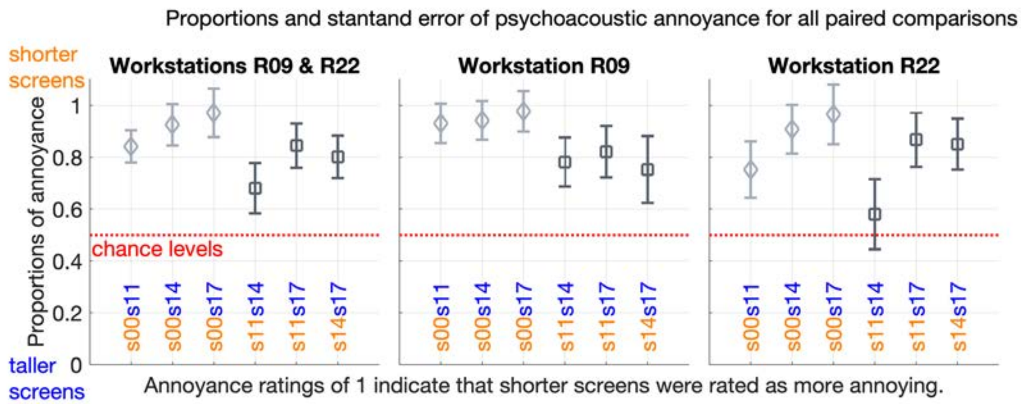

Figure 2: Proportions of annoyance for each group of paired comparisons. The y-axis is assigned to the upper end to shorter screens by convention. The red dotted line at 0.5 represents chance levels.

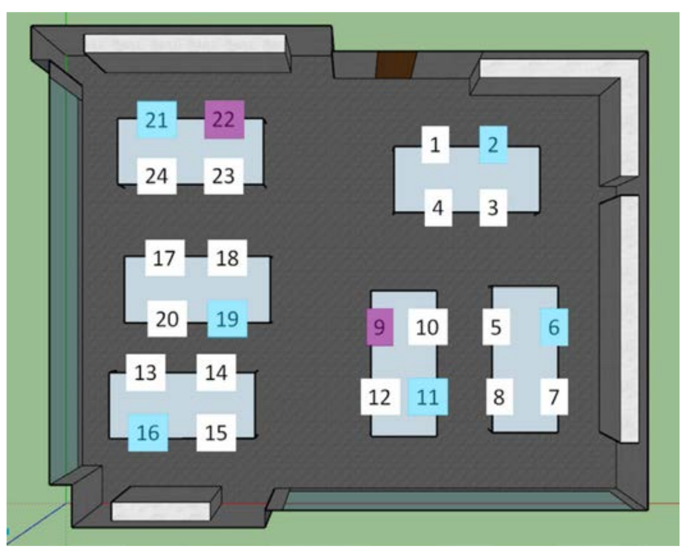

Figure 3: Color coding of the source-receiver positions used in the listening test (purple is the receiver and cyan the source).

CONCLUSION

In this investigation, the aim was to assess the acoustic conditions of a demonstrator open-plan office using a holistic approach. A multitude of acoustic measurements, simulations and psychoacoustic evaluations were conducted to assess the effects of a virtual implementation of acoustical treatments to subjective percepts of psychoacoustic annoyance.

The findings reported here shed new light on the effect of different screen heights on subjective responses of annoyance. The results show that even a minimum acoustical treatment (110 cm) is a preferred choice in comparison to the untreated version of the office. Furthermore, there is increased uncertainty for the paired comparison between 110-140 cm screen heights. This incorporates the implications of a holistic and educated approach when suggesting an optimal screen height for an open-plan office. A simulated result from a CAD acoustic software might not be a one-way decision. More specifically, a screen height of 110 cm is below eye-sight and facilitates visual communication and collaboration in work environments. This evidence along with the results from the listening test suggests that an acoustic consultant should take a decision based on the test case of the office in question. For example, if the open space in question is a university library, a screen height of 170 cm might be the best option. In contrast, an open plan office with knowledge workers is more likely to be improved with a short screen height (e.g. 110 cm). That height is a better choice in comparison to a no-treatment scenario or the 140 cm screen height, which does not facilitate visual communication when seated.

Taken together, these findings suggest a role for acoustical treatments in promoting the conditions of open space work environments. Whereas the limitations of a web-based listening test may have contributed to the results, it was a necessary route due to the COVID-19. The limitations of forced-choice testing might also be reflected in the results. The alternative of a no-opinion response was excluded because it also introduces biases related to participants' lazy responses. Furthermore, it introduces difficulties in the ranking of percepts that cannot be quantified as single-dimensional.

Future studies should look more into the effect of familiarity of responders with open-plan offices. Do employees adapt to acoustic treatments and more noise is 'acceptable'? The precise mechanism is yet to be elucidated.

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This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under the Marie Sklodowska-Curie grant Agreement, number 721536

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